

Ten milliparsec-scale structure of the nucleus region in Centaurus A

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Abstract

We present the results of a VLBI Space Observatory Programme (VSOP) observation of the subparsec structure in Centaurus A at 4.9 GHz. The observation produced an image of the sub-parsec jet components with a resolution more than 3 times better than images from previous VLBI monitoring campaigns at 8.4 GHz and more than 2 times better than the previous 22 GHz studies. Owing to its proximity, our Centaurus A space-VLBI image is one of the highest spatial resolution images of an AGN ever made — 0.01 pc per beam — comparable only to recent 43 GHz VLBI images of M87. The elongated core region is resolved into several components over 10 milli-arcseconds long (0.2 pc) including a compact component of brightness temperature 2.2×10^{10} K. The counter jet was detected: if we assume jet–counterjet symmetry, a relatively slow jet speed, and a large viewing angle, as derived from previous observations, the image allows us to investigate the distribution of ionized gas around the core, which is opaque at this frequency due to free-free absorption. We also analyze the jet geometry in terms of collimation. Assuming the strongest component to be the core, the jet opening angle at $\sim 5000r_s$ from the core is estimated to be $\sim 12^\circ$, with collimation of the jet to $\sim 3^\circ$ continuing out to $\sim 20,000r_s$. This result is consistent with previous studies of the jet in M87, which favor MHD disk outflow models. Future space VLBI observations at higher frequencies will probably be able to image the collimation region, within $1000r_s$ of the center of Centaurus A, together with the accretion disk itself.

Key words: galaxies: active — galaxies: individual (Centaurus A)
 — techniques: interferometric

1. Introduction

Centaurus A (NGC 5128) is the closest radio galaxy, at a distant of only 3.4 Mpc (Israel 1998). This proximity allows higher resolution imaging than can be obtained for more distant galaxies, resulting in Centaurus A being one of the most important targets for the study of jet formation and collimation mechanisms in active galactic nuclei (AGNs). The estimated mass of the central black hole, based on infrared observation of a 20pc central disk, is $2.0 \pm 1.4^{3.0} \times 10^8 M_\odot$ (Marconi et al. 2001). Observations with VLBI arrays can obtain images of the nuclear radio source in this galaxy with a linear resolution of 0.02 pc ($\sim 1000r_s$) for a 1 mas angular resolution.

Previous VLBI monitoring of Centaurus A shows that the subparsec-scale jet has components with a slow proper motion away from the nucleus of approximately 0.1c, while irregular episodes of rapid evolution within jet component suggests that the underlying flow of the jet is much faster, and probably greater than 0.45c (Tingay et al. 1998, Tingay, Preston and Jauncey 2001). Considering the likely jet speed and the jet-to-counterjet surface brightness ratio (Jones et al. 1996), Tingay et al. (1998) concluded that the sub-parsec scale jet is inclined to our line of sight by between 50° and 80°. These results are in contrast with a recent analysis based on the VLA observations for 100pc scale jet, which suggest apparent subluminal motions of approximately 0.5c and a significantly smaller angle to the line of sight of $\sim 15^\circ$ (Hardcastle et al. 2003). Using the VLBA at 43 GHz, Kellermann et al. (1997) measured the size of the compact radio nucleus of Centaurus A to be about 0.5 mas (0.01 pc) by fitting the visibilities with a circular Gaussian component. However the coverage of (u, v) plane with the VLBA alone is severely limited because the source is so far south, and they were not able to construct an image of the nucleus.

To study the nature of nuclear region, we conducted a space VLBI (VSOP) monitoring program of Centaurus A, observing with the HALCA space telescope (Hirabayashi et al. 1998) at 4.9 GHz and 1.6 GHz, from mid 1999 to mid 2000 when the (u, v) -coverage was optimal (Horiuchi, Meier and Preston 2002). Space-ground baseline fringes of Centaurus A were detected for the first time, although the signal to noise ratio became rapidly smaller as the space baseline length became larger than one Earth diameter. These observations produced images of the sub-parsec jet components with a resolution several times better than images in an ongoing 8.4 GHz monitoring campaign and a few times better than 22 GHz studies.

In this paper we highlight the highest quality image obtained, from the observation on 2000 August 6, due to sensitive telescopes, especially the phased VLA and ATCA, which joined the ground telescope array. Owing to its proximity, our Centaurus A space-VLBI images are some of the highest spatial resolution images ever made of an AGN — 0.01 pc per beam — comparable only to the 43 GHz VLBI images of M87 (Junor et al. 1999). We discuss the structure of the core region and the implications of the remarkably collinear jet extending from the core region to the 1 pc scale.

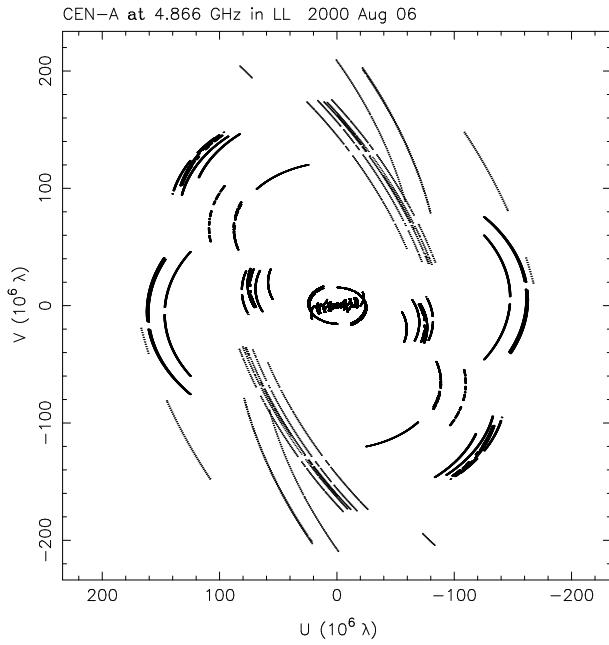


Fig. 1. The (u, v) -coverage of the VSOP observation. Solid lines are for ground baselines and dotted lines (the long, straight diagonal tracks) are space baselines where fringe-fitting was successful.

2. Observations and Results

The observations presented here were conducted as a part of VSOP observation series to monitor the evolution of Centaurus A over 18 months starting on January 1999, mainly at 4.9 GHz. The observing frequency was at 4.866 GHz for 16 MHz bandwidth with 2-bit sampling. The observation was divided into two parts for different correlators. From 2000 August 6 UT 21:00 to August 7 UT 02:30, the participating ground telescopes were six of the 10 VLBA stations (FD, KP, LA, MK, OV, PT), the VLA and ATCA (Narrabri), with the data correlated at the Socorro VLBA correlator. From August 7 UT 03:00 to 13:00, the ground telescopes were the ATCA, Ceduna, Mopra, Hartebeesthoek and VLBA-Mauna Kea, with the data correlated at the Penticton S2 correlator. The space data obtained with the HALCA satellite was downloaded and recorded in VLBA format at the Green Bank tracking station for the first part of the observation, and in S2 format at the Madrid, Tidbinbilla and Goldstone stations for the latter part.

The data from the correlators were exported into the Astronomical Image Processing System (AIPS) as FITS files, amplitude calibrated, fringe-fitted, and averaged before standard VLBI imaging procedures in Difmap. The source was highly resolved on the longer baselines, and fringe-fitting for HALCA was only successful for projected baselines up to an earth diameter. This was consistent with the previous VSOP series on this source (Fujisawa et al. 2000) in which no space fringes were detected. The (u, v) coverage of the data used for imaging is shown in Figure 1. The image obtained from this (u, v) coverage is shown in Figure 2. The rms

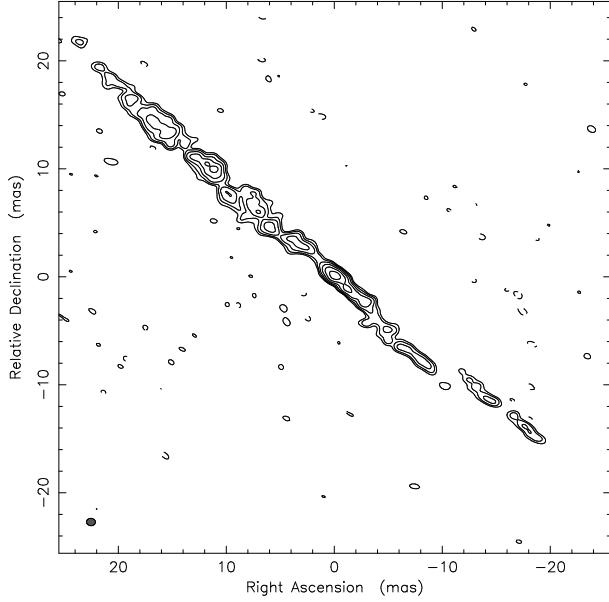


Fig. 2. The full resolution VSOP image of the inner 40 mas around the peak. The FWHM of the restored beam is 0.827×0.68 mas at a P.A. of 86.2° as indicated in the small filled circle in the bottom left hand corner. Contours are drawn at -2, 2, 4, 8, 16, 32 and 64% of 0.182 Jy/beam, the peak flux density in the map.

noise level of the space VLBI image is 0.90 mJy/beam for the peak level of 182 mJy/beam, corresponding to a dynamic range of 200. The image obtained from the ground baselines only (solid lines in Figure 1) is shown in Figure 3. This image yields an rms noise level of 0.57 mJy/beam and a peak level of 167 mJy/beam, hence a dynamic range of 293.

In both images the jet is remarkably linear and oriented along the position angle $\sim 51^\circ$ with several components visible. The brightest part of the jet has an elongation northeast and a counter jet to the southwest. It is not easy to distinguish between the core and the jet with a single epoch, single frequency map for such a complicated source. The nucleus region of Centaurus A is affected substantially by both synchrotron self-absorption and free-free absorption, which are both frequency-dependent effects. Tingay and Murphy (2001) registered images of 2.2 GHz, 5.0 GHz and 8.4 GHz restored using an average restoring beam of 19×6 mas at position angle 4° , in order to estimate the free-free optical depth and the intrinsic spectral index. They found that the core has a comparable flux to the jet at 5 GHz, while the core dominates the jet at 8 GHz and the core is substantially absorbed and invisible at 2.2 GHz. To identify the core region we compared Tingay and Murphy's 5.0 GHz VLBA image at 1999 May 4 (Figure 4-a) and our image (Figure 4-b), both restored with the same beam as originally used in Tingay and Murphy (2001). In spite of the 15 month separation between these two

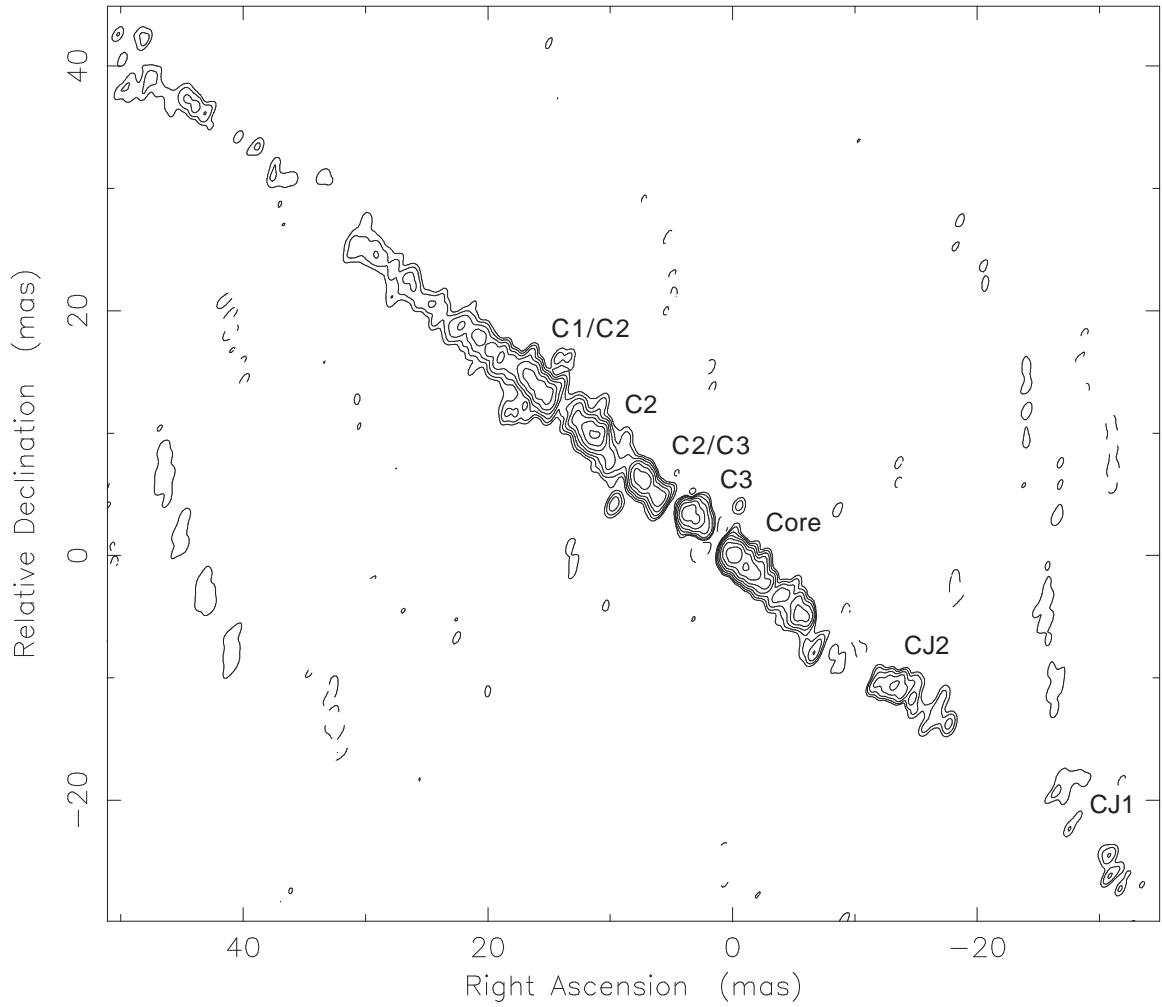


Fig. 3. The image obtained from the ground telescopes only. The FWHM of the restored beam is 1.19×0.61 mas at P.A. -27.5° . Contours are drawn at $-0.8, 0.8, 1.6, 3.2, 6.4, 12.8, 25.6$ and 51.2% of 0.167 Jy/beam, the peak flux density in the map.

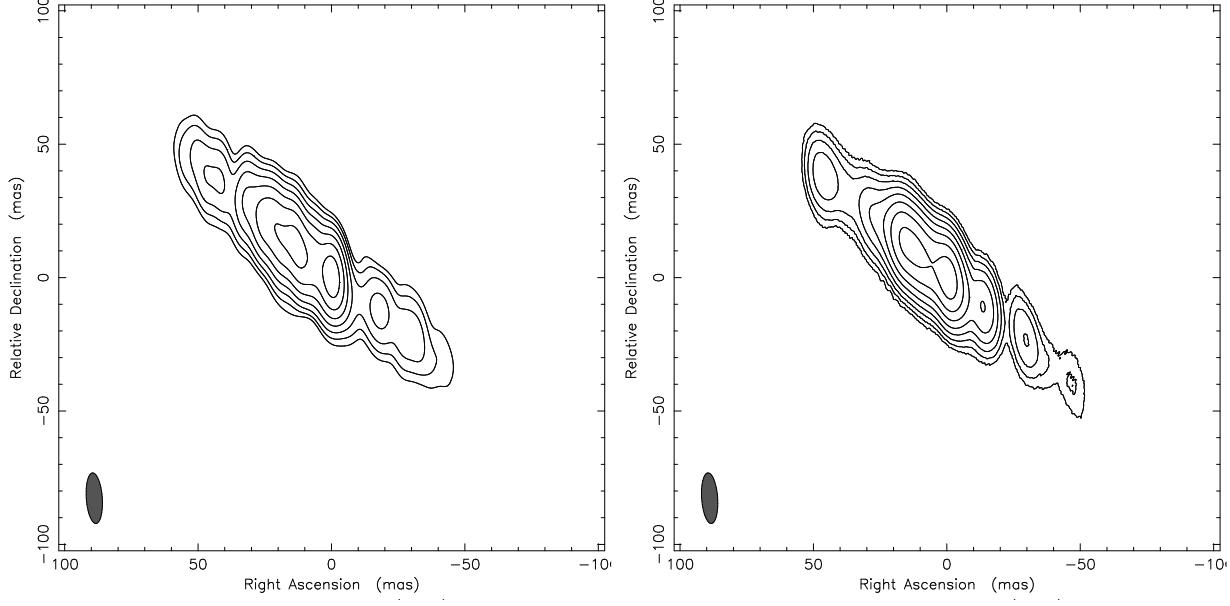


Fig. 4. (a) left: 5.0 GHz VLBA image at 1999 May 4 (Tingay and Murphy 2001), (b) right: Image from the same data for Figure 3. Both images are restored with the larger beam of 19×6 mas at position angle 4° as used by Tingay and Murphy (2001) for spectral analysis. Contour levels are -1, 1, 2, 4, 8, 16, 32 and 64% of 0.854 Jy/beam, the peak flux density in the map, for (b), and -0.5, 0.5, 1, 2, 4, 8, 16, 32 and 64% of 0.839 Jy/beam for (b).

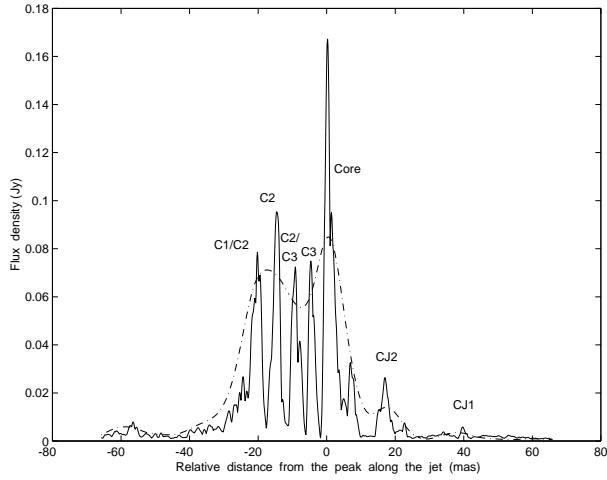


Fig. 5. Surface brightness profile image along the P.A. 51° corresponding to the jet axis. The line represents the ground baseline image shown in Figure 1 and the dotted line represents that convolved with the larger beam shown in Figure 4, with the amplitude scaled to 0.1 times for comparison. The identification of the components for the Core, C1, C2, C3, CJ1 and CJ2 are adopted from Tingay, Preston and Jauncey (2001).

observations, the images appear to be very similar at this resolution, hence we concluded that the brightest part around the phase center in our image corresponds to the core region, in which the 2.2 GHz flux would be substantially absorbed as observed by Tingay and Murphy (2001).

The surface brightness of both the original image (Figure 3) and the lower resolution image (Figure 4-b) is illustrated in Figure 5 as a “slice” profile along the jet. Assuming that the elongated region that includes the brightest part is the core, the identification of large scale components over 60 mas, C1, C2, C3 CJ1 and CJ2, are adopted from comparison to the previous VLBI monitoring (Tingay et al. 1998, Tingay, Preston and Jauncey 2001). In our image there are 4 distinctive bright parts in the jet for C1, C2 and C3, which leave some ambiguity in the identification. Hence we tentatively denote a component between possible C2 and C3 as ”C2/C3”, and another component in northeast of C2 as ”C1/C2”. In the previous VLBI monitoring (Tingay et al. 1998, Tingay, Preston and Jauncey 2001), both C1 and C2 show elongated linear structure along the jet and the fitted lengths are sometimes up to around 20 mas depending on the observing epoch. It is likely that our observation resolves those two regions into more than two components.

Fujisawa et al. (2000) claimed to have found a large bending of jet close to the position of component C3 from the VSOP observation at 5 GHz in January 1998. Our observation had a much better (u, v) coverage and two times better resolution perpendicular to the jet: no such bending is recognizable in our image. However because of -43° declination of Centaurus A and the positional relation between the VLBA and the other southern hemisphere ground telescopes, our data still suffer large (u, v) holes over the intermediate resolution range of 50-100 $M\lambda$, especially at position angles similar to the jet direction. To prove the reliability of our Centaurus A map as shown in Fig.3 we made a couple of tests: 1) We retained clean components for only the 5 brightest features, from the core region through the C1/C2 components in the map, and examined how well they alone fit the data. We observed that about 40% of the flux on the shortest baselines correspond to the residuals while the visibilities on the longer baselines fit the model very well, indicating there is significant structure that is not accounted for in the simple map. Finally we exported the retained clean components to the original uv-data before clean-selfcalibration iteration and confirmed that the residual map clearly showed weaker features such as the counter jet. 2) We tried model-fitting the visibility data and see how many components are definitely required before there is ambiguity as to what additional components (if any) should be added. We found up to 12 required components whose positions are reasonably consistent with the features in the original map as shown in Fig.3.

To quantify the structure of the nuclear region of Centaurus A, the image obtained using the array of ground telescopes only (Figure 3) was analyzed using the AIPS task JMFIT to modelfit each sub-component with a Gaussian profile. This procedure is more reliable than fitting models to the (u, v) data when the high-resolution visibilities are too complex to fit the model meaningfully. Table 1 shows the parameters obtained from the modelfit. The brightest

Table 1. Models for the image shown in Figure 3

Flux (Jy)	Radius (mas)	θ (deg)	Major axis (mas)	Axial ratio	ψ (deg)	T_b 10^{10} K	ID
0.478	0.00	0.00	1.52	0.49	50.6	2.19	Core1
0.235	1.98	-139.1	2.76	0.17	53.5	0.91	Core2
0.370	4.96	-141.5	2.13	0.62	80.7	0.68	Core3
0.121	7.14	-139.0	1.75	0.63	47.6	0.32	Core4
0.274	5.10	45.0	1.84	0.58	61.3	0.72	C3
0.326	9.39	49.3	2.59	0.32	45.9	0.78	C2/C3?
0.416	15.11	48.5	2.10	0.45	45.4	1.09	C2
0.403	20.79	49.1	2.44	0.45	44.0	0.78	C1/C2?
0.118	16.8	-141.5	2.17	0.55	77.8	0.24	CJ2
0.040	40.3	-139.7	5.79	0.17	0.65	0.04	CJ1

core feature around the phase center is modeled with 4 components labeled with Core1, Core2, Core3 and Core4. The brightness temperature T_b is also derived for each component and listed in Table 1.

3. Discussion

3.1. Identification of the core and the brightness temperature

We resolved the core region into several components. We also successfully detected a few components of the counter jet. As we described earlier, it is difficult to identify the core itself from only one epoch at a single frequency. This is especially the case if we have no other images to compare at similar resolution. If the jet and the counter jet are intrinsically symmetric and ejected from the core symmetrically, we should be able to know the location of the core as the origin of both the jet and counter jet. Under the simple beaming model for symmetric jet system with equal and constant bulk and pattern speed, the ratio of the apparent distances from the core of equivalent components in the approaching and receding jet, in terms of the bulk velocity of material in the jet ($\beta = v/c$) and the angle to the line of sight θ , is $D = (1 + \beta \cos\theta) / (1 - \beta \cos\theta) \sim 1.1$ for the typical values of $v \sim 0.1c$ and $\theta \sim 60^\circ$ adopted from the monitoring results of Tingay et al. (1998) and Tingay, Preston and Jauncey (2001) for the jet components C1 and C2. This gives an upper limit of displacement of the core from apparent geometrical center which is only applicable for outer jet components such as C1 and C2, and there would be no such displacement expected for inner components such as C3 since no significant motion has been recognized in the monitoring. The derived mild upper limit of D for Centaurus A is in contrast with other radio source 3C 84 in which a relatively large value of $D = 1.8$ is derived (Walker, Romney and Benson 1994), suggesting a larger jet speed ($v \sim 0.33c$)

and a smaller viewing angle ($\theta \sim 32^\circ$) for the value of jet-counterjet brightness ratio R they measured. If CJ2, located around 20 mas from the core, is the counter part of C2, then $R \sim 4$. This is consistent with the 8 GHz result discussed by Jones et al. (1996) for their beaming model.

The brightness temperature of the brightest component, Core1, is 2.2×10^{10} K while Core2, the second most compact component in the core region, has a brightness temperature of 9.1×10^9 K (Table 1). Both the brightness temperatures are well below the inverse Compton limit. It is not yet clear how the free-free optical depth varies around the core at this resolution, but it is likely that the core region is substantially absorbed, hence much brighter intrinsically. Assuming that the values derived by Tingay and Murphy (2001) are still applicable at this resolution, we can adopt the optical depth of 0.2 at 5 GHz and intrinsic spectral index of 2.0 for the unresolved nuclear component, in which case the observed flux is expected to have been decreased to $\sim 7\%$ of the original flux, indicating the intrinsic brightness temperature $\sim 3.1 \times 10^{11}$ K and 1.3×10^{11} K for Core1 and Core2 respectively. These values are still below the inverse Compton limit, but close to the limit calculated based on equipartition arguments (Readhead 1994).

Kellermann et al. (1997) measured a core size of 0.5 mas for Centaurus A with non-imaging visibility analysis of a few hours VLBA data taken at 43 GHz in April 1994, fitting the visibilities with a circular Gaussian component. They also deduced the lower limit of the brightness temperature to be about 10^{10} K for the peak visibility amplitude of about 5 Jy. The (u, v) distance range of our 5 GHz data is similar to the VLBA at 43 GHz and we obtained the same rough source size and brightness temperature for our 5 GHz core component with ten times weaker flux. Although we measured similar values for the core brightness temperature for the 5 GHz core, if we consider the optical depth of 0.2 at 5 GHz and the intrinsic spectral index of 2.0, an estimated "equivalent" intrinsic flux density at 43 GHz for the 5 GHz core is about 8 times larger than the 43 GHz core flux density measured in April 1994. This difference may be attributed to significant variability of the core that has been observed at high frequencies such as 22 GHz and 43 GHz (Botti and Abraham 1993).

3.2. Comparison with M87

Marconi et al. (2001) have estimated the mass of the central black hole in Centaurus A to be $2.0 \pm 1.4 \times 10^8 M_\odot$, from infrared spectra obtained at the Very Large Telescope. The Schwarzschild radii, r_s , for this mass is approximately 0.00002 pc, hence the spatial resolution of our observation 0.6 mas (0.012 pc at 3.4 Mpc distance) corresponds to $600r_s$. Junor et al. (1999) presented a 43 GHz VLBI image of the jet in M87 (at a distance of 14.6 Mpc) on an angular scale of 0.12 mas, corresponding to a spatial scale of 0.009 mas, or $30r_s$ for the estimated black hole mass of $3 \times 10^9 M_\odot$. Their image shows a remarkably broad jet having an opening angle of $\sim 60^\circ$ near the center, with strong collimation of the jet occurring at $\sim 30 - 100r_s$

from the center, and collimation continuing out to $\sim 1000r_s$. This seems to favor MHD disk wind models. In a seminal paper on this subject, Blandford and Payne (1982) demonstrated by simple analysis that ionized gas frozen onto magnetic field lines at the surface the accretion disk will be unstable to outflow, if the angle of the field line to the vertical is $\theta \geq 30^\circ$, in which case the material will be flung outward along the field lines by centrifugal force. The large opening angle of the jet seen at $30r_s$ distance from the center of M87 seems to suggest that the jet originates from such a disk outflow (Junor et al. 1999, see also Meier et al. 2001 for a review). Because of the high linear scale resolution available to resolve the region around the black hole, Centaurus A is another ideal candidate for studies of the jet collimation mechanism.

Tingay, Preston and Jauncey (2001) examined their Centaurus A data to see if they could measure a jet opening angle on scale greater than their resolution ($\sim 1000r_s$) but no evidence for a significant jet opening angle could be seen. In our image the jet appears to be significantly collinear from the core region to 60 mas (1pc). If we assume Core1 is the core, the jet opening angle of the first jet component C3 is $\sim 12^\circ$ at a distance of 0.1 pc, or $\sim 5000r_s$ from the core. Interestingly, this angle and r_s distance are very similar to the results of the 5 GHz VSOP observations of M87 included in Junor et al. (1999, Figure 3) as a part of the plot showing jet full opening angle as function of distance from the core, although our distance of C3 from the core corresponds to 0.1 pc and their distance corresponds to 2 pc from the core. Figure 6 shows all the measured jet opening angles for the components in the jet, excluding the counter jet and the core sub-components. This result indicates that our observation marginally resolves the lower end of the collimation region in the Centaurus A jet. Future space VLBI missions such as VSOP-2 at 22 GHz and 43 GHz (Hirabayashi et al. 2004) will probably be able to image the collimation region, within $1000r_s$ from the center of Centaurus A, together with the accretion disk itself.

4. Conclusion

We have presented a high resolution VLBI image of the nearest radio galaxy Centaurus A at 4.9 GHz on 2000 August 6 that shows the sub-parsec scale structure of the jet and the core on scales from 0.5 to approximately 50 milli-arcseconds from the core (0.01–1 pc projected linear distance). The elongated core region is resolved into several components over 10 mas long. Model-fitting analysis have shown that the strongest peak is a compact component with the brightness temperature 2.2×10^{10} K. The jet-to-counterjet brightness ratio is approximately 4 for the jet around 20 mas from the core, consistent with previous observations at 2.3 and 8.4 GHz. Assuming the strongest component to be the core, the jet opening angle at $\sim 5000r_s$ from the core is estimated to be $\sim 12^\circ$ with collimation of the jet to $\sim 3^\circ$ continuing out to $\sim 20,000r_s$, suggesting that collimation of jet occurs inside this region similar to that seen in M87.

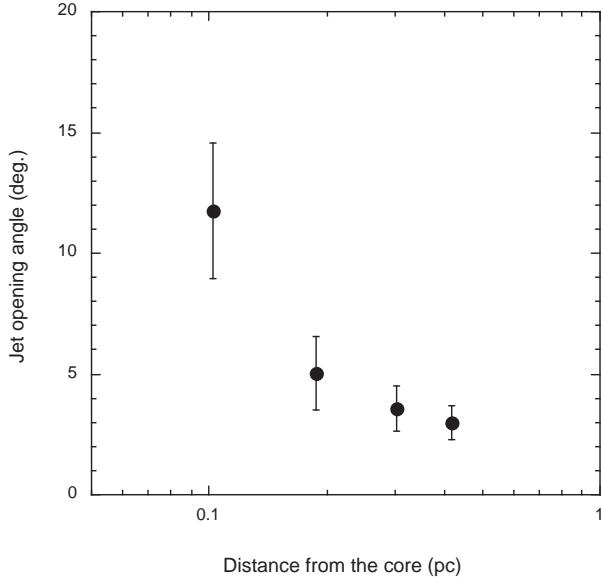


Fig. 6. Jet full opening angle as function of distance from the core for Centaurus A. Error bars represent angles corresponding to one fourth of beam size to indicate uncertainties of measurement.

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5. Conclusions

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